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Global warming and United States landfalling hurricanes

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[1] A secular warming of sea surface temperature occurs almost everywhere over the global ocean. Here we use observational data to show that global warming of the sea surface is associated with a secular increase of tropospheric vertical wind shear in the main development region (MDR) for Atlantic hurricanes. The increased wind shear coincides with a weak but robust downward trend in U.S. landfalling hurricanes, a reliable measure of hurricanes over the long term. Warmings over the tropical oceans compete with one another, with the tropical Pacific and Indian Oceans increasing wind shear and the tropical North Atlantic decreasing wind shear. Warmings in the tropical Pacific and Indian Oceans win the competition and produce increased wind shear which reduces U.S. landfalling hurricanes. Whether future global warming increases the vertical wind shear in the MDR for Atlantic hurricanes will depend on the relative role induced by secular warmings over the tropical oceans. **Citation:** Wang, C., and S.-K. Lee (2008), Global warming and United States landfalling hurricanes, *Geophys. Res. Lett.*, *35*, L02708, doi:10.1029/2007GL032396.

1. Introduction

[2] An increase in global ocean temperatures can cause sea levels to rise and change the quantity and regional patterns of precipitation. It is also argued that there may be changes in the frequency and intensity of extreme weather events, although it is difficult to connect specific events to global warming. Atlantic hurricane activity has been shown to have largely increased in frequency and intensity since 1995 [e.g., *Goldenberg et al.*, 2001; *Emanuel*, 2005; *Webster et al.*, 2005]. In particular, the 2005 hurricane season is the most active year on record, with 28 named tropical storms in the Atlantic basin and 15 of them reaching hurricane intensity. The recent increase in Atlantic hurricane activity has fueled a debate on the role of global warming in the increase [e.g., *Goldenberg et al.*, 2001; *Emanuel*, 2005; *Webster et al.*, 2005; *Landsea*, 2005]. Obviously, the relationship between global warming and Atlantic hurricanes is both scientifically and socially important. This paper uses observational data to demonstrate that the attribution of the recent increase in Atlantic hurricane activity to global warming is premature and that global warming may decrease the likelihood of hurricanes making landfall in the United States.

2. Global Warming and Vertical Wind Shear

[3] The improved extended reconstructed sea surface temperature (SST) data [*Smith and Reynolds*, 2004] for the past 153 years (1854 to 2006) is used to examine warming or cooling over the global ocean. An empirical orthogonal function analysis is performed on the annual mean SST. The spatial pattern and temporal variation of the first mode, which represents a global warming mode, are shown in Figure 1. There is warming almost everywhere over the global ocean, with exceptions in the region south of Greenland, in the North and South Pacific, and in the region around Antarctica where cooling occurs. In particular, large warmings occur in the tropical Pacific, Atlantic, and Indian Oceans. The warming pattern in the tropical Pacific is similar to that of the interannual phenomenon of El Niño, with maximum warming in the equatorial eastern Pacific. The basin-wide warming is consistent with expected effects of an increase in greenhouse gas concentrations, and the regional cooling may be suggestive of radiative effects of aerosols or oceanic natural variability. The temporal variation (Figure 1b) shows that the global ocean is mainly cooling before the 1940s and warming after the 1940s.

[4] One important factor for controlling Atlantic hurricane activity is the vertical wind shear between the upper and lower troposphere in the main development region (MDR) within the 10°N–20°N latitude belt that stretches from West Africa to Central America. An enhancement in tropospheric vertical wind shear is associated with a quiet hurricane season in the Atlantic basin, as it inhibits the organization of deep convection, and *vice versa* for a reduction in vertical wind shear. The relationship of vertical wind shear to global warming is examined by regressing vertical wind shear onto a temporal variation of global warming of SST (Figure 2). A positive regression appears in the MDR for Atlantic hurricanes and a negative regression is north of the MDR. The positive regression in the MDR indicates that global warming is associated with an increase of the vertical wind shear, thus inhibits atmospheric convection and disfavors the formation and development of Atlantic hurricanes.

[5] The positive wind shear regression in the MDR of Figure 2 extends northwestward to the United States via the Gulf of Mexico, despite a small value. Does this have any implication for a hurricane to be intensified and make a landfall? To address this question, we first discuss the relationship between vertical wind shear and U. S. landfalling hurricanes. The regression of the vertical wind shear during June–November onto U.S. landfalling hurricanes is shown in Figure 3. Figure 3 shows a large negative wind shear regression located in the MDR, consistent with the fact that a reduction (enhancement) of vertical wind shear favors (disfavors) hurricane activity. It also shows that the negative wind shear regression in the MDR extends toward

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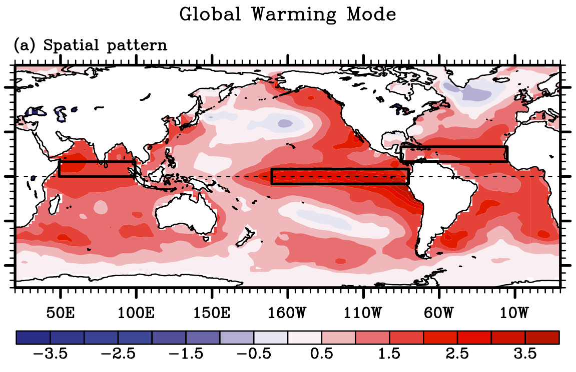

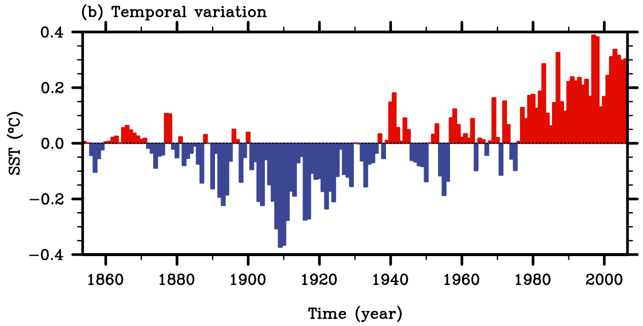

Figure 1. (a) The spatial pattern and (b) temporal reconstruction for the first empirical orthogonal function (EOF) mode, representing global ocean warming. The EOF mode is presented by reconstructing its spatial pattern and expansion coefficient of time series. The temporal variation is the spatial average over the global ocean of the modal reconstruction of SST (in unit of °C) rather than the more confusing temporal amplitude (without unit) from which it is derived. This is equivalent to multiplying the EOF time series with the average of its spatial eigenfunction over the global ocean. This scaling does not change the character of the time series. The spatial pattern is constructed from the regression coefficient (°C per °C) between the reconstructed time series and SST. Three boxes are marked in the tropical North Atlantic, eastern Pacific, and Indian Oceans where warmings of the sea surface are examined for their influence on Atlantic hurricane activity.

to the United States via the Gulf of Mexico, creating a condition that favors a hurricane to be intensified and make landfall in the United States. Thus, the northwestward extension of the positive wind shear regression, associated with global warming in Figure 2, may reduce the formation and development of hurricanes which would result in fewer U.S. landfalling hurricanes.

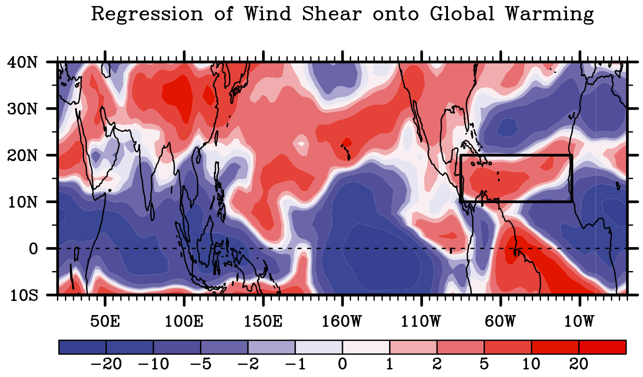

Figure 2. Regression coefficient (m/s per °C) of vertical wind shear onto the temporal variation of global warming of SST in Figure 1b. The vertical wind shear is calculated as the magnitude of the vector difference between winds at 200 mb and 850 mb during the Atlantic hurricane season (June to November), using NCEP-NCAR reanalysis data. The box represents the main development region (MDR) for Atlantic hurricanes (85°W–15°W, 10°N–20°N). The 95% significance level (based on Student's t-test assuming independent observations) for the regressions averaged over the MDR is ±2.78 m/s per °C.

[6] To further verify the variation of vertical wind shear, a time series of vertical wind shear in the MDR for Atlantic hurricanes is computed (not shown). The vertical wind shear indeed shows a strong upward linear trend since 1949 when modern atmospheric data became available, in addition to interannual and multidecadal variations. The upward trend in wind shear is supported by a recent study [*Nynerg et al.*, 2007] that shows an increased trend in the wind shear (reconstructed using corals and marine sediment cores) since 1880 in the Caribbean Sea. In addition, *Vecchi and Soden* [2007] report an increase in the vertical wind shear over the Caribbean Sea under global warming scenarios for the 21st century, by analyzing a suite of coupled ocean-atmosphere model outputs (the models are forced by an emission scenario of atmospheric CO_2 concentration of 720 parts per million by year 2100). The consistency of the paleoclimatic proxy data, modern observational data, and future model projections suggests that the increase of the vertical wind shear in the MDR for Atlantic hurricanes, associated with global warming, is a robust feature.

3. Variations of U.S. Landfalling Hurricanes

[7] Our Figure 2 shows that global warming is associated with an increase of the vertical wind shear in the MDR, which suppresses the formation and development of Atlantic hurricanes and results in fewer landfalling hurricanes. A natural question to ask is whether observed Atlantic hurricane activity shows a long-term downward trend. The

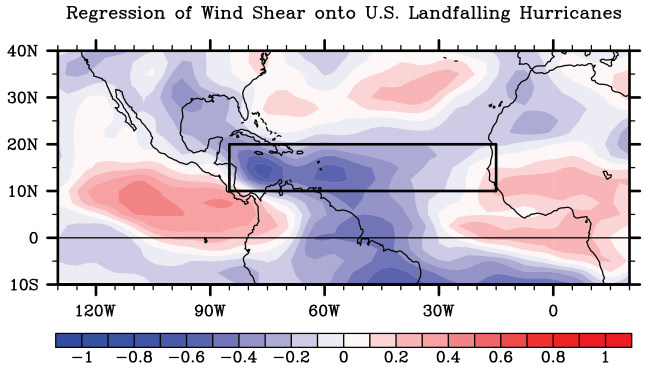

Figure 3. Regression coefficient (m/s per number) of vertical wind shear during June–November onto U.S. landfalling hurricanes. The box represents the main development region (MDR) for Atlantic hurricanes (85°W–15°W, 10°N–20°N). The 95% significance level (based on Student's t-test assuming independent observations) for the regressions averaged over the MDR is ±0.35 m/s per number.

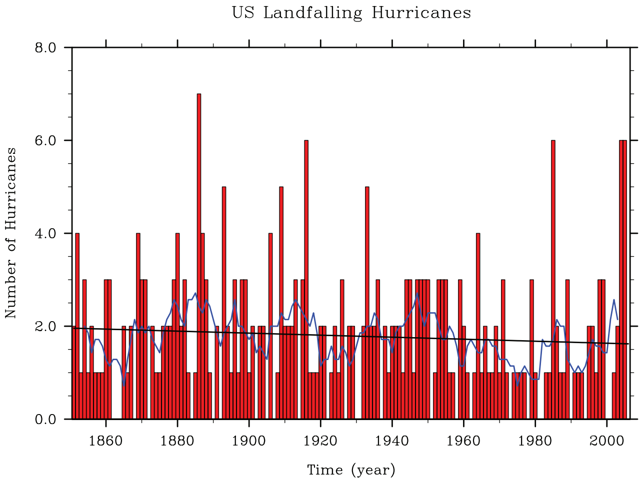

Figure 4. The number of U.S. landfalling hurricanes from 1851 to 2006. The black straight line is the linear trend that is fitted to the U.S. landfalling hurricane time series ($y = -0.00217x + 1.96$). The blue line is the seven-year running mean of U.S. landfalling hurricanes, emphasizing longer (than interannual) timescale variations. The downward trend is below the 95% significance level.

validity of hurricane activity trends is the subject of intense debate [e.g., *Emanuel*, 2005; *Webster et al.*, 2005; *Landsea*, 2005, 2007; *Chan*, 2006; *Klotzbach*, 2006; *Kossin et al.*, 2007]. Based on unadjusted hurricane data, Atlantic hurricane activity from the late 19th century or the early 20th century to the present shows an upward trend. However, it is probable that hurricanes were undercounted before the era of aircraft reconnaissance (around the mid-1940s) and satellite technology (the mid-1960s) since hurricanes over the open ocean during that time can be rarely detected. If one takes into account the potential "missed" hurricanes over the open ocean, the upward trend decreases substantially or even disappears [*Solow and Moore*, 2002; *Landsea*, 2007; Vecchi and Knutson, manuscript submitted to *Journal of Climate*, 2007], not inconsistent with a secular increase of the vertical wind shear observed in the MDR.

[8] Given hurricane data problems, by far the most reliable Atlantic hurricane measurement over the long term is the number of U.S. landfalling hurricanes since it excludes hurricanes over the open ocean (which never make a landfall) that can be hardly detected before aircraft reconnaissance and satellite eras [*Landsea*, 2007]. The hurricane reanalysis database of HURDAT at NOAA AOML (http://www.aoml.noaa.gov/hrd/data_sub/re_anal.html) is used to generate a time series of U.S. landfalling hurricanes for the period 1851–2006 (Figure 4). U.S. landfalling hurricanes show a multidecadal variability, with enhanced numbers during 1875–1895, 1905–1915, 1930–1955, and after 1995 and reduced numbers in between. In addition to the multidecadal variability, the number of U.S. landfalling hurricanes also shows a weak downward trend (see the fitted line by a least-squares method in Figure 4). The downward trend is statistically not significant (below 95% significance level), but robust because it is independent of the beginning of the linear fit as long as the fitted hurricane data covers at least a full cycle of the Atlantic multidecadal oscillation (AMO). For example, U.S. landfalling hurricanes still show a downward trend with data starting from the 1900s or the 1940s. However, U.S. landfalling hurricanes display an upward trend from the 1970s because the period of 1970–2006 covers only a half cycle of the AMO, i.e., from the cool AMO phase of 1970–1990 to the warm AMO phase of 1995–2006. The transition from the cool to warm phases of the AMO may increase Atlantic hurricane activity.

[9] Downward trends in Atlantic hurricanes or global hurricanes are also reported by using other hurricane datasets. *Nynerg et al.* [2007] construct a record of major Atlantic hurricanes over the past 270 years using proxy data. They find that major hurricanes decrease gradually from the 1760s until the early 1990s and that the recent increase is not unusual compared with other periods of high hurricane activity. *Kossin et al.* [2007] create a reanalysis hurricane database that accounts for artificial trends due to historical evolution of the way hurricanes are detected. Their reanalysis hurricane data shows a downward trend in the power dissipation index for global hurricanes (all basin hurricanes), thus modifying the previous results of a global hurricane increase [*Emanuel*, 2005; *Webster et al.*, 2005]. The accumulated cyclone energy index, which has been used to measure tropical cyclone activity, is also observed to have a downward trend for global hurricanes over the past two decades when consistent satellite imagery has been available [*Klotzbach*, 2006].

4. Relative Role of the Tropical Oceans

[10] Next we examine and discuss how and why global ocean warming produces an increase of the vertical wind shear in the MDR for Atlantic hurricanes. The climate response to SST is primarily forced by tropical SST [e.g., *Sutton and Hodson*, 2007], and Figure 1a shows a large ocean warming occurring in the tropics. Therefore, we focus on the influence of the tropical Atlantic, Pacific, and Indian Oceans. The time series of the SST anomalies in the MDR, the tropical eastern Pacific, and the tropical Indian Ocean during the Atlantic hurricane season are calculated and normalized by their regional maxima. Vertical wind shear is then regressed onto these SST time series, as shown in Figure 5. Local ocean warming in the MDR reduces the vertical wind shear in the MDR (Figure 5a), consistent with numerical modeling results [*Sutton and Hodson*, 2007; *Wang and Lee*, 2007]. However, warmings in the tropical Pacific and Indian Oceans produce an opposite effect, i.e., they increase the vertical wind shear in the MDR for Atlantic hurricanes (Figures 5b and 5c), consistent with the result of an atmospheric general circulation model [*Latif et al.*, 2007]. This effect is due to warm tropical SSTs altering the heating distribution, which changes atmospheric circulation patterns. In particular, warm water in the tropical eastern Pacific increases the vertical wind shear in the tropical North Atlantic, primarily through its influence on the upper-level westerly flow [*Gray*, 1984]. Therefore, the tropical oceans compete with one another for their impacts on the vertical wind shear over the MDR for Atlantic hurricanes. Since the effects of warmings in the tropical Pacific and Indian Oceans overcome that of the local warming in the tropical North Atlantic, the net result is an

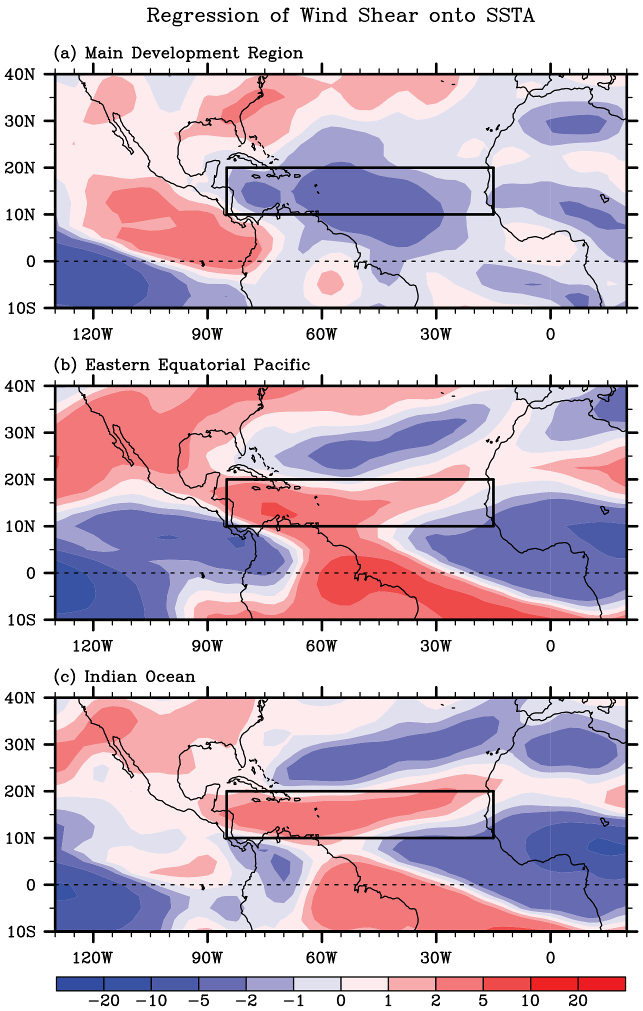

Figure 5. Regression coefficients of vertical wind shear onto the SST anomalies during June–November in (a) the main development region (MDR) (85°W–15°W, 10°N–20°N), (b) the eastern equatorial Pacific (170°W–80°W, 5°S–5°N), and (c) the tropical Indian Ocean (50°E–100°E, 0°–10°N). The vertical wind shear is calculated as the magnitude of the vector difference between winds at 200 mb and 850 mb during the Atlantic hurricane season of June–November, using NCEP-NCAR reanalysis data from 1949 to 2006. The box represents the MDR for Atlantic hurricanes. The 95% significance levels (based on Student's t-test assuming independent observations) for the regressions averaged over the MDR are ±2.14, ±1.87, and ±1.42 for Figures 5a, 5b, and 5c, respectively.

increase of the vertical wind shear in the MDR. This may explain why global ocean warming in Figure 1 is associated with an increase of the vertical wind shear in the MDR for Atlantic hurricanes.

[11] This study suggests that the spatial distribution of global ocean warming is important for determining the vertical wind shear in the MDR for Atlantic hurricanes. Whether future global warming increases Atlantic hurricane activity will probably depend on the relative role induced by secular warmings over the tropical oceans. For example, if the effects of warmings in the tropical Pacific and Indian Oceans cannot overcome that of Atlantic warming, global warming may favor landfall incidence for the United States. Therefore, model projections of ocean warming patterns under future global warming scenarios may be crucial in predicting future Atlantic hurricane activity. Additionally, it should be recognized that anthropogenic global warming has a pervasive influence on both oceanic and atmospheric temperatures and circulation as well as water vapor, all of which affect tropical cyclones in complex and not yet fully understood ways. A better understanding of these factors and of the influence of natural climate variability on tropical cyclones is needed.

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